Journal of Geography and Cartography 2024, 7(2), 6588.
https://doi.org/10.24294/jgc.v7i2.6588

Article

A perennial controversy: The St. Peter Sandstone of the American Midwest

Greg Brick

Earth & Environmental Sciences Department, University of Minnesota, Minneapolis, MN 55455, USA; bric0004@umn.edu

CITATION

Brick G. A perennial controversy: The St. Peter Sandstone of the American Midwest. Journal of Geography and Cartography. 2024; 7(2): 6588. https://doi.org/10.24294/jgc.v7i2.6588

ARTICLE INFO

Received: 24 May 2024
Accepted: 12 July 2024
Available online: 1 August 2024

Abstract: The St. Peter Sandstone of the American Midwest is presented today in textbooks as a simple and unproblematic example of "layer-cake geology." The thesis of this paper is that the very simplicity of St. Peter Sandstone has made it challenging to characterize. In widely separated states, the sandstone appeared under different names. Several theories about how it formed began to circulate. The story of the St. Peter is not only the story of the assemblage of a stratigraphic unit over a vast area during three centuries, but also the role the study of the provenance of this unit played in the development of sedimentology in the early twentieth century, research that was made all the more challenging by its "simple" mineralogy. Indeed, the St. Peter has been controversial since it was first described.

Keywords: St. Peter Sandstone; quartz arenite; Minnesota; Neptunism; Abraham Gottlob Werner; sedimentology; particle size analysis

1. Introduction

The St. Peter Sandstone of the American Midwest is presented today in textbooks as a simple and unproblematic example of "layer-cake geology." A largely horizontal formation of variable thickness, but averaging 30 m, this cratonic sheet sand underlies 585,000 square km in thirteen states. A brief lithological description is appropriate. The formation has been divided into various members according to the geological survey of the state concerned. In the state of Minnesota, locality of the St. Peter type section, the upper Tonti Member is the one usually exposed in cliff faces. The sandstone is fine to medium-grained, well sorted, and poorly cemented. The beds are internally structureless, with occasional cross-stratification. The lower, Pigs Eye Member, is less often exposed in outcrop [1]. The current consensus is that the sandstone was deposited in the nearshore of a shallow, transgressing epicontinental sea during Ordovician times, 450 million years ago, presenting a combination of eolian, fluvial, and marine characteristics [2]. It was the last great period of quartz deposition on the vegetation-free craton during the Paleozoic.

Its mineralogy, too, is usually presented as simple and unproblematic. Over much of the region, the sandstone is more than 99% quartz and dazzling white in outcrop. Its lack of cementation leads to its pronounced friability, or readiness to crumble, which led to it being compared to loaf sugar in the early days. Its most important economic uses have included glass manufacture, as an ingredient of mortars, and for foundry molds [3]. In various places, it also serves as an aquifer, a natural gas reservoir, and most recently, for carbon dioxide sequestration [4].

But geologists have long held mixed feelings about St. Peter. Kentucky geologist Willard R. Jillson declared in 1938 that "The Saint Peter is still an imperfectly known unit in American stratigraphy. Perhaps it will always be" [5]. Mazzullo and Ehrlich stated that, "The St. Peter Sandstone of southeastern Minnesota is a classic example of homogeneous, featureless, problematic lithology" [6]. Simo et al. lamented that "the formation was maddingly difficult to interpret" [7]. The most widely used textbook of Minnesota geology today, in its description of the St. Peter, asserted that, "The answers are not yet in. As scientists are so prone to say, further study is necessary" [8]. And as recently as 2014, Konstantinou et al. affirmed that, "Despite numerous studies, the century-long debate on how these [quartz] arenites formed is still unresolved" [9].

The thesis of this paper is that the very simplicity of the St. Peter Sandstone has made it difficult to characterize. In widely separated states, the sandstone appeared under different names. Several theories about the nature of this rock began to circulate. The story of St. Peter is not only the story of the assemblage of a stratigraphic unit over a vast area during three centuries, but also the role the study of the provenance of this unit played in the development of sedimentology in the early twentieth century, research that was made all the more challenging by its "simple" mineralogy. Indeed, the St. Peter has been controversial since it was first described.

2. The assemblage of a stratigraphic unit

Ever since the late seventeenth century, reports about a white-cliff-forming rock had come back from the wilderness in the interior of North America. The French explorers Jolliet and Marquette must have been the first Europeans to see the St. Peter Sandstone at the mouth of the Wisconsin River, where it enters the Mississippi, while canoeing the Fox-Wisconsin River portage route in 1673. At the junction of the Wisconsin and Mississippi rivers, they would have been confronted by the towering cliffs of St. Peter Sandstone on the western side of the river at what is now Pikes Peak State Park, in the state of Iowa. However, no description of the rock itself was left by these early explorers [10]. In 1682, another French explorer, René-Robert Cavelier, Sieur de La Salle (1643–1687), constructed Fort St. Louis atop Starved Rock, Illinois—cliffs of what is now known to be St. Peter Sandstone **(Figure 1**). They called this "Le Rocher", meaning "The Rock" [11]. La Salle sent Father Louis Hennepin (1626–1704) to explore the Upper Mississippi River, and Jillson asserted, somewhat misleadingly, that "Father Hennepin first gazed upon … the Saint Peter Sandstone at the Falls of Saint Anthony" [5]. The problem is that Hennepin himself did not mention the sandstone in his description of the waterfall in 1680 [12]. And based on my own personal observation, the sandstone is not especially prominent at this particular location.

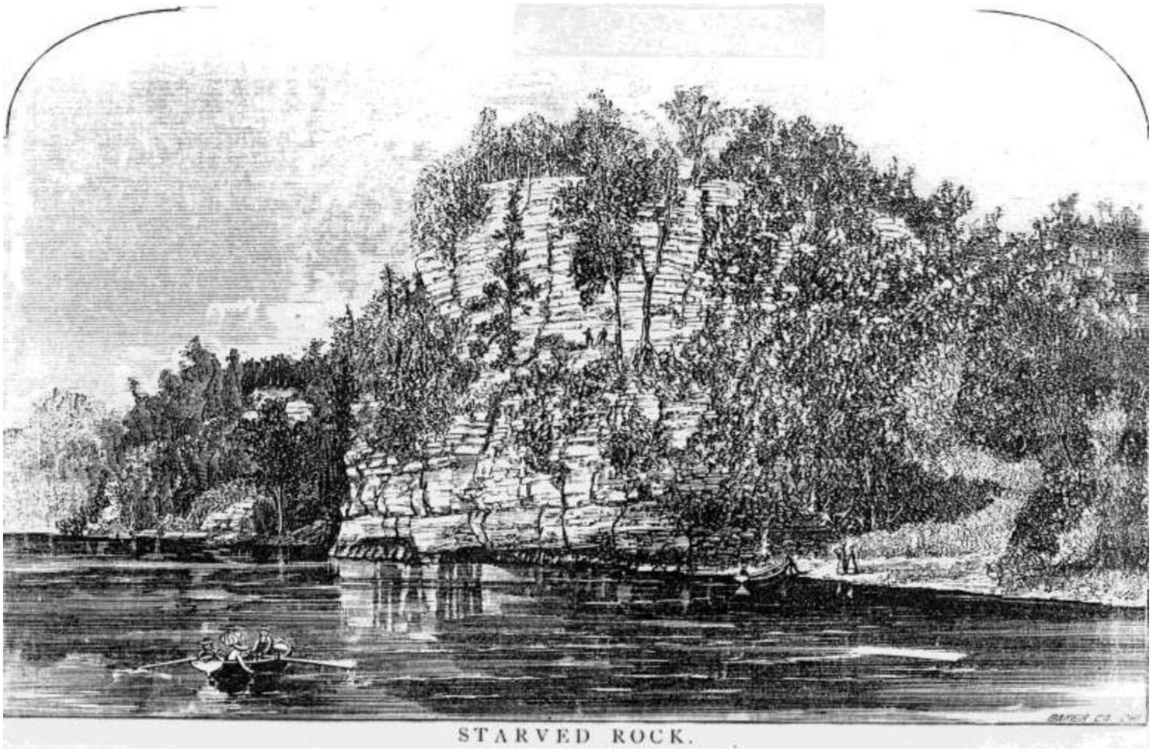

Figure 1. Starved Rock, a prominent historical landmark of St. Peter Sandstone on the Illinois River in the state of Illinois, known to Europeans since 1682 (From Kett [13]).

The first good St. Peter descriptions in the historical record are from the British colonial explorer Jonathan Carver (1710–1780), who traversed the Upper Mississippi in 1766–1767. Ascending the Mississippi River north of Prairie du Chien, Wisconsin, he reported that: “The mountains upon the Mississippi abound with a kind of stone as easily wrought as wood when newly taken out of the ground but hardens in the air. Much of it is white as snow and would serve for building in the best manner. Others have the color and quality of grindstone” [14]. Carver subsequently described the “white stone” at Carver’s Cave. In what is perhaps the most heavily quoted passage from Carver’s best-selling “Travels”, we read that:

> “About thirty miles below the Falls of St. Anthony, at which I arrived the tenth day after I left Lake Pepin, is a remarkable cave of an amazing depth. The Indians term it Wakon-teebe, that is, the Dwelling of the Great Spirit …. I found in this cave many Indian hieroglyphicks, which appeared very ancient, for time had nearly covered them with moss, so that it was with difficulty I could trace them. They were cut in a rude manner upon the inside of the walls, which were composed of a stone so extremely soft that it might be easily penetrated with a knife: a stone everywhere to be found near the Mississippi” [15].

In 1820, Fort Snelling was established at the confluence of the Minnesota and Mississippi rivers, atop bluffs of this snowy white sandstone (**Figure 2**). What is now the nearby city of St. Paul, capital of Minnesota, was established in the 1840s at a place known as “White Cliffs” among the Native peoples [16]. The type locality was described by geologist David Dale Owen (1807–1860) in 1847 from outcrops at this confluence (see below). Due to the construction of extensive revetments at the fort in the years since then, these outcrops are no longer accessible.

Figure 2. The white cliffs of St. Peter Sandstone at the type section of the formation, Fort Snelling, 1844 (Courtesy Minnesota Historical Society).

Landscape artist Henry Lewis (1819–1904), preparing a moving panorama for public display, painted scenes along the Mississippi River from St. Anthony Falls to the Gulf of Mexico, many of which were included in his book, “Views of the Mississippi”, originally published in German in 1854. Lewis calls the St. Paul cliffs “The Cornice Cliffs,” perhaps an allusion to how erosion has sculpted them into quasi-architectural forms [17]. It’s important to note that in most places, where the St. Peter Sandstone manifests itself as cliffs, its soft, crumbly nature requires the presence of a hard limestone caprock, the Platteville Limestone, to protect it from erosion. Thus, a fanciful comparison to columns and entablatures seemed appropriate.

In the neighboring state of Wisconsin, the white cliffs also drew early attention, especially along the Mississippi River, an important steamboat route. One of Owen’s assistants during the geological reconnaissance of the Chippewa Land District was John Locke, who drafted a geological cross-section at Prairie du Chien in 1839 [18] (**Figure 3**).

In other states, widely separated from the type section in Minnesota, encounters with the St. Peter Sandstone appeared under different names and guises. George C. Swallow (1817–1899) reported a “Saccharoidal Sandstone” in his 1855 geological survey of Missouri [19] (**Figure 4**). Harvard geologist Nathaniel Southgate Shaler (1841–1906) identified what he called the “Calciferous Sand Rock” in the drilling logs of deep wells in Kentucky in 1877, and it was not until 1909 that its true identity was known [5].

Figure 3. John Locke's 1839 geological cross-section of the Mississippi cliffs, depicting the village of Prairie du Chien, Wisconsin, on the river bottoms. The St. Peter is here described as "soft sugar-like sandstone" (Courtesy Wisconsin Historical Society).

Figure 4. Saccharoidal Sandstone in the cliffs of the Pomme de Terre River, near Bolivar, Missouri, in 1855, from Swallow [19]. There were several units with the same name, creating confusion.

Indeed, the drilling of artesian wells, beginning in the late nineteenth century, greatly extended the known area of the St. Peter Sandstone. The first comprehensive map of these occurrences of white cliffs in the American Midwest was by Charles P. Berkey in 1906 [20]. It was seen that the outcrop of the sandstone is not broadly continuous, though the sea from which it was deposited was of vast extent. Ultimately it evolved into the map published by George A. Thiel in 1935 [21] **(Figure 5**). The sandstone manifests itself as an outcrop in the states of Arkansas, Illinois, Iowa, Minnesota, Missouri, and Wisconsin. Deep wells revealed its presence under Indiana, Kansas, Kentucky, Michigan, Nebraska, Ohio, and Tennessee. In 1938, Jillson [5] summarized that "Roughly, the paleogeographic pattern of deposition of the Saint Peter Sandstone is that of an ellipse," the east-west axis of which he estimated at 1,300 km, and the north-south axis as 950 km. In the states of Ohio, Kentucky, and Tennessee, where it serves as a host rock for oil and gas plays, the sandstone was of considerable economic interest [5].

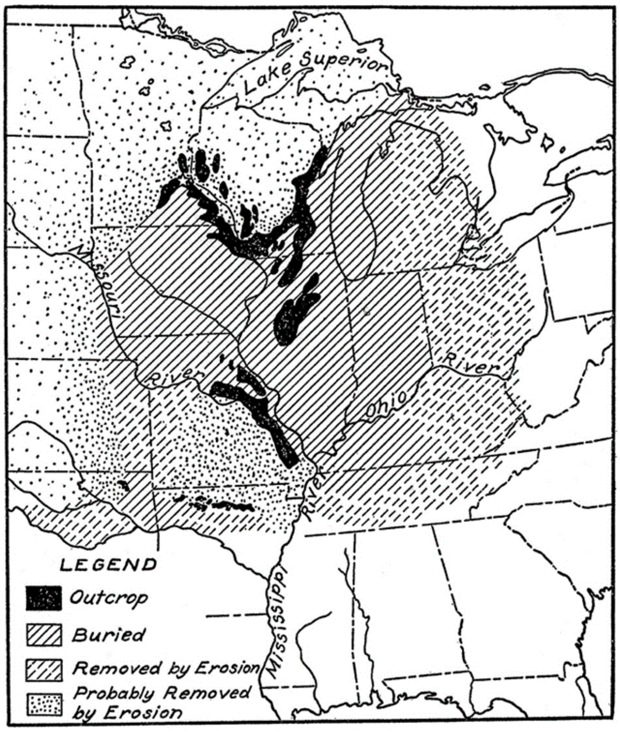

Figure 5. "Distribution of the St. Peter Sandstone" (modified from Thiel [21]). The type section at Fort Snelling, Minnesota, is located among the northernmost outcrop areas shown on the map, as indicated by the star. While this sandstone underlies much of the American Midwest, its vast subsurface extent was not realized until the widespread drilling of artesian wells.

The St. Peter Sandstone underwent wild swings of stratigraphic interpretation over the years. According to the Wernerians (see below), this sandstone fell into the "secondary or horizontal class of rocks." In 1825, William H. Keating (1799–1840) assigned this sandstone to the Lias [22], which in modern stratigraphy would place it in the Jurassic Period. By 1835, however, Roderick I. Murchison (1792–1871) had unveiled his new Silurian System in Europe. Traveling up the Minnesota River by canoe, George W. Featherstonhaugh (1780–1866), the first to use the title "U.S.

Geologist," became an early adopter, applying modern concepts and terminology from England [23]. "Featherstonhaugh was probably the first in America to use the terms Cambrian and Silurian in a geologic column" [24]. He was "highly scornful" of Amos Eaton (1776–1842), the prominent American stratigrapher, who "knew little about the importance of fossils" [25]. Based on "a great variety of fossils, such as orthoceras, bellerophon, fucoides, orthis," Featherstonhaugh classified "the great sandstone beds of the country," seen at Fort Snelling, as Silurian in age [26]. But not until 1903 did the U.S. Geological Survey officially adopt the name Ordovician, thereafter applied to these rocks [27].

Another early adopter of Murchison's terminology was David Dale Owen, the second "U.S. Geologist," who imported the Silurian label to the American Midwest in numerous geological surveys [28]. By the time Owen actually published the name "St. Peter Sandstone," after its type locality on the St. Peter's (now Minnesota) River in 1847, understanding of the stratigraphic position of the layer had been transformed [29,30]. The paleontologist James Hall was able to correlate trans-Appalachian geologic units, including the St. Peter, with the more familiar units of the New York Geological Survey, beginning with a traverse of the Ohio River valley in 1841. He found that sedimentary formations thinned out westwardly, one aspect of his discovery of the craton [31].

3. A problematic lithology

"Every theory of the Earth published in England between Steno's theory in 1671 and Kirwan's theory in 1799 has one feature in common: they all claim that a large proportion of the Earth's rocks are precipitates laid down in some chaotic fluid" [32]. The assumption that sea sands had been chemically precipitated from seawater was widespread in previous centuries; for example, the famous botanist Linnaeus held this belief [33].

Keating served as mineralogist on Major Stephen H. Long's 1823 expedition to the source of the St. Peter's River. He concluded, on the basis of grain shape, that the St. Peter Sandstone, at what was to become Owen's type section, was a chemical precipitate from seawater [22]. This appears to be an echo of the Neptunist teachings of Abraham Gottlob Werner (1749–1817). Precipitation of rock layers from a primitive ocean was a signature Neptunist teaching at the Freiberg Mining Academy in Saxony (**Figure 6**).

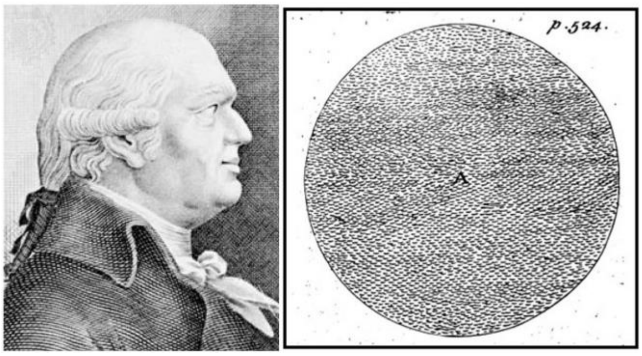

Figure 6. Abraham Werner, father of Neptunism (left) and his water world, showing the Universal Ocean, from Brick [34].

Werner's influence on early American geology was pervasive. Prominent American Wernerians of that time included Eaton, Benjamin Silliman (1779–1864), and Parker Cleaveland (1780–1858) [35]. William Maclure (1763–1840), dubbed the "Father of American Geology" by Silliman, used the Wernerian scheme to map the eastern United States [36]. Indeed, Ospovat characterized the years from 1785 to 1829 as "the Wernerian Era of American geology" [35]. Even after Wernerian concepts had fallen out of favor with geologists themselves, they continued to be presented in popular works, such as John Hinton's "History and Topography of the United States", as late as 1852 [37].

"All American geological maps produced before 1825 were based on the Wernerian scheme" [38]. Maclure's famous 1809 map of the geology of the United States, revised in 1817, extended as far west as the Mississippi River [39,40]. American geology was thus initially interpreted in Wernerian terms, which entailed mapping the extent of the Primitive, Transition, Secondary, and Alluvial formations. The American Midwest was at the western fringes of Maclure's map and was shown as undifferentiated "Secondary". But according to Schneer, "The principal error in Maclure's map was in classifying the Paleozoic strata of the plateaus between the Mississippi River and the Appalachian Mountains as secondary on the basis of their attitude (nearly flat) and their lithology. They should have been Transition rocks in his scheme" [41].

Nonetheless, on Major Long's previous expedition through the American Midwest to the Rocky Mountains in 1819, Werner was cited as the chief authority in matters geological [35]. Most of Long's expeditions deployed Wernerian explanations for the geological phenomena encountered [42]. The geologist of this earlier expedition, Edwin James (1797–1861), extended Maclure's Wernerian mapping program to the land between the Mississippi River and the Rocky Mountains [37,43].

The fullest account of Keating's encounter with the St. Peter Sandstone on 9 July 1823 is contained in his "Narrative of an Expedition to the Source of St. Peter's River":

> "Immediately under this bed of [Platteville] limestone, in parallel stratification, we observed the [St. Peter] sandstone, which constitutes the principal mass of the bluff, being about sixty feet in thickness. It is a very friable stone, and in some cases the grains, of which it is formed, are so loosely united that it appears almost like sand. Every fragment, if examined with care, seems to be a regular crystal, and we incline much to the opinion that this sandstone must have been formed by a chemical precipitation and not by mere mechanical deposition. The process of its formation may have been a very rapid one, such as is obtained in the manufacture of fine salt, and to this may be attributed the circumstance of its loose texture. The grain is very fine; its colour is white, sometimes a little yellowish, in which case it resembles in texture, colour, &c. the finer varieties of Muscovado sugar. The loose texture of the rock is probably the cause of its presenting but few indications of stratification" [22].

Although Keating did not use the words "pure" or "purity" in the context of the St. Peter Sandstone, the purity concept, later to become part of petrographic rhetoric, was attributed to him by Frederick W. Sardeson in 1896 [44]. Owen appears to be the first, in 1852, to use the word "pure" consequent upon an actual chemical analysis, which showed "but two-tenths of one per cent of foreign matter," making it appropriate for "the glass-houses at Pittsburg" [30].

Keating's speculations about the St. Peter Sandstone projected Wernerian interpretations farther west than ever before. The "primitive ocean" from which the sandstone supposedly precipitated, named the "Saint Peter Sea' by Berkey, was epicontinental, extending northward from what is now the Gulf of Mexico [20].

While Werner's concept of basalt crystallizing from sea water had lost favor even among fervent Wernerians like Keating by this time, the chemical precipitation of sedimentary rocks from sea water appears to be the last surviving petrological concept of Werner among American geologists. With Keating, we see an actual reversion to chemical precipitation, a Wernerian mechanism, to account for a rock layer. Keating asserted that the St. Peter sand grains resemble tiny crystals. He had elsewhere described examining a sand sample with a microscope during the expedition [22], but he did not mention a microscope at Fort Snelling, and it is unknown what magnification (if any) he employed to view the grains. But it would not be the first time he had made a crystallographic blunder [45]. The Wisconsin geologist Thomas C. Chamberlin (1843–1928) later warned against precisely this error, emphasizing the necessity for distinguishing the angular grains of the St. Peter Sandstone from "freely-forming quartz crystals" [46]. The other St. Peter grain shape commonly found is rounded, and these also indicate a detrital origin because chemical precipitation would have produced an interlocking fabric [47].

Impressed by the discovery of the enormous siliceous sinter deposits of the Iceland geysers, some chemists, such as Richard Kirwan (1733–1812), became convinced that, if Werner's Universal Ocean was hot and alkaline, the deposition of silica was indeed feasible [48]. The German chemical geologist Gustav Bischof (1792–1870) asserted "investigations prove that sandstone strata have been formed, not only from quartzose detritus, but, also from siliceous deposits from water" [49], though it appears he was referring to the deposition of siliceous cements, not the body of the rock unit. This distinction is important because Bischof was a proponent of the so-called "neo-Neptunist" school of thought [50]. Among them, "particularly from the French and German-speaking parts of Europe, the old Wernerian idea of an aqueous origin for crystalline rocks was by no means defunct, well into the second half of the nineteenth century" [51]. While the precipitation of silica from seawater to form siliceous ooze and, ultimately, chert is a familiar process, enormous quartz sandstones like the St. Peter are not known to form in this way [52].

Keating did attract direct support from several American scientists. The Wisconsin antiquarian and topographer Increase A. Lapham (1811–1875) investigated the St. Peter in the last days of its anonymity before Owen formally bestowed a name upon it. "The sandstone is mostly pure, and white as the driven snow," he reported. "The grains appear to be perfect quartz crystals, and not beach sand smoothed and ground by the action of water and then hardened into rock" [53].

James Hall (1811–1898) and Josiah D. Whitney (1819–1896) were prominent geologists who endorsed Keating's notion of the chemical origin of the St. Peter Sandstone but put the emphasis on lack of fossils rather than presence of crystalline facets.

The origin of these immense accumulations of silicious matter in so pure a form and with such peculiarities of lithological character is a matter of great theoretical interest. It has been generally assumed, without much examination of the subject, that all such sandstones were originally formed by mechanical agencies, the material being supposed to have gradually accumulated from the grinding down of previously existing quartzose rocks. The facts collected above, however, seem rather to point to chemical than mechanical causes, as having been the chief agents in the deposition of the sandstones. If these silicious strata, developed over such an extensive surface and with such a thickness as they are, were the result of the trituration of the azoic rocks which everywhere underlie them, and it is difficult to conceive of any other source from which the material could have been obtained, unless we adopt the chemical theory, we can hardly understand how such an amount of quartzose sand could have been accumulated, without its containing, at the same time, a considerable quantity of detritus which could be recognized as having come from the destruction of the schistose, feldspathic and trappean rocks that make up the larger portion of the azoic series, wherever it has been examined. The uniform size of the grains of which the sandstone is composed and the tendency to the development of crystalline facets in them are additional facts that suggest the idea of chemical precipitation rather than of mechanical accumulation [54].

As late as 1862, Hall and Whitney reiterated that "no vestige of an organism, either of plant or animal, has been observed" in the St. Peter [55].

The grand finale of the chemical precipitation theory, however, took place in 1871, nearly a half century after Keating's original observations. John Murrish (1820–1886), a geologist working in the lead regions of southwestern Wisconsin, applied the Iceland geyser analogy directly to the St. Peter Sandstone, emphasizing "the fact that very different physical conditions prevailed then to what we find now." He seemed enamored with the "little crystals of quartz." "I have sometimes thought," he wrote, "that I would give almost anything if I could procure some of those crystals in their magnified forms as cabinet specimens" [56]. The historian Goerge P. Merrill, however, dismissed Murrish as a man of "slight training" who "was led into many errors" [18].

Soon after, in 1876, Newton H. Winchell (1839–1914) found a fossil brachiopod, "Lingulepis", at the very top of the St. Peter Sandstone in Minnesota, and subsequently Sardeson found many molluscan fossils within the lower third of the sandstone, again in Minnesota [44]. "They dispel the idea," Winchell asserted, "of the possible chemical origin of the St. Peter Sandstone, as an oceanic precipitate" [57].

4. New developments in sedimentology

Ultimately, three explanations emerged to account for the purity of the St. Peter Sandstone, and they would have implications for the understanding of its provenance. The first was Keating's chemical precipitation, which, although not directly linked to the issue of purity by him, was certainly in the forefront for his supporters, especially Hall and Whitney [54]. The second was Sardeson's "percolating waters," whereby "the Saint Peter has simply had all soluble material washed out of it" [44]. The third was Berkey's concept of recycled sandstones, whereby "wind and water" had winnowed away the impurities [20]. While there was certainly truth in Sardeson's conjecture, it was Berkey's that would get the most play as the field of sedimentology advanced.

A new method was being developed that would have a significant impact on the study of the St. Peter Sandstone. "Between about 1930 and 1950 particle size analysis seems to have been the single most important technique ... The method of particle size analysis was formulated and developed by two pioneer American sedimentologists, J. A. Udden and C. K. Wentworth, between 1890 and 1920" [58]. The subsequent maturation of sedimentology, with the application of statistical analysis to the St. Peter Sandstone, led to the realization that "the uniform size of the grains" of which Hall spoke was an unwarranted generalization when the "uniformity coefficient" was actually calculated [59].

Charles L. Dake (1883–1934) spent most of his career at the Missouri School of Mines and Metallurgy in Rolla [60]. His doctoral thesis, "The Problem of the St. Peter Sandstone," undertook to examine the "problem" of where the sand constituting this sandstone came from [59]. Implicit in the title was the assumption that it was, of course, a mechanical sediment, and the paper reads as one long argument against an eolian origin for the sandstone. Dake adopted Berkey's suggestion of a recycled sandstone, emphasizing a specific candidate for its precursor, the Cambrian-aged Potsdam sandstone of the Great Lakes region [59]. "A belt of Potsdam," he wrote, "fringes the pre-Cambrian shield" [59]. Berkey favored "the Basal Sandstone," which included the Potsdam along with other units [20]. According to Dake:

> "The purity of the St. Peter Sandstone, while very remarkable, as compared with that of average sandstones, is, in respect to content of clay, iron, mica, heavy minerals, and carbonate, not sufficiently different from that of associated marine sandstones to demand any essentially different explanation of origin; the degree of difference actually existing being satisfactorily accounted for by assuming its derivation from one of the older, already well-sorted sandstones, the Potsdam" [59].

Dake had employed elementary statistical arguments, but the rapid development of sedimentology soon added new parameters. George A. Thiel (1892–1979), long-time chairman of the geology department at the University of Minnesota, had undertaken to clarify the subject in the 1930s [61]. Thiel's classic study, "Sedimentary and Petrographic Analysis of the St. Peter Sandstone," published in 1935, was the first to fully describe the St. Peter statistically [62]. On the basis of the more rigorous procedures and reasoning of the day, Thiel broke with the monocyclic paradigm that had characterized St. Peter genealogy: "The accessory minerals in the St. Peter Sandstone suggest also that the sands have passed through several cycles of transportation and attrition ... The common rock-forming ferro-magnesian minerals are no longer present" [21]. Hard, durable accessory minerals such as "zircon, rutile, and tourmaline," were the only ones to survive. Ironically, the impurities were now driving the argument about purity.

Moreover, Thiel unseated the favored candidate for precursor status by introducing the "average median diameter." "If the St. Peter sands were derived from the Potsdam sandstones, as suggested by Dake, Lamar, and Giles, one would expect to find these Cambrian sandstones composed, for the most part, of sands coarser than, or at least as coarse as, the St. Peter sands," whereas the St. Peter grains had a larger average median diameter than their supposed source in the Potsdam. On the basis of samples from "the Kettle River sandstone taken at [the town of] Sandstone, Minnesota," he was able to identify a more suitable precursor [21]. It was the lower part of Berkey's "Basal Sandstone," what we now call the Hinckley Sandstone, of Upper Precambrian age [63].

Finally, Thiel broached a topic that returns us to the origins of the Keating controversy, perhaps providing an alternative resolution (literally). Keating claimed to have seen in the St. Peter grains "a regular crystal." But Thiel observed secondary growths on St. Peter grains, which often result from re-solution of surrounding grains: "Much of the present angularity of the larger quartz grains in the St. Peter sands is due to changes in shape resulting from fracturing or is due to recrystallization and enlargement produced by secondary growth," adding that "secondary growth tends to reconstruct quartz grains to their original hexagonal crystal structure" [21]. Or, as Krynine expressed it: "Pseudo-angularity produced by secondary silica overgrowths on the grains of quartzitic rocks should not be mistaken for original angularity" [64]. While Henry Clifton Sorby (1826–1908) was the first to describe overgrowths on quartz grains in 1880 [65,66], the possibility remains that Keating's real significance was in being the first to observe quartz overgrowths, mistaking them for primary growth (**Figure 7**).

Figure 7. Grains of St. Peter Sandstone, from Brick [3].

Many changes occurred in the field of sedimentology following Thiel, but the thread of purity arguments about the St. Peter Sandstone tapered off after the hey-day of particle-size analysis. There was a transition away from the word "purity," which was part of an "industrial-commercial parlance" [62], towards terms denoting petrological maturity, in particular, chemical maturity (as contrasted with textural maturity). Beginning in the 1940s, with the famous compositional triangles for sandstone classification stemming from the work of F. J. Pettijohn and P. D. Krynine, among others, the word purity rarely appears [67], although some sedimentologists continued to speak informally of "clean sands" [64]. In the new ternary diagrams, the St. Peter Sandstone is plotted as a quartzose sandstone or quartz arenite.

In recent decades, provenance studies of the St. Peter Sandstone have focused on newer methods. To determine the ultimate source of detrital zircons in the St. Peter, Johnson and Winter [68] studied source ages, finding two clusters: 1.1 billion years ago (suggestive of Midcontinental Rift origin) and 2.7 billion years ago (suggestive of the granite-greenstone terrane of the Superior Province). In both cases, the ultimate source is thought to be Precambrian felsic plutonic rocks such as granite. To determine the immediate source of the sandstone, however, they undertook isotopic studies of quartz grains, which contain zircon microinclusions. Their data indicates a sedimentary source, the lower Paleozoic quartz arenites, corroborating the results of past studies, especially those of Tyler, published in 1936 [69].

5. Conclusion

A vast region of white cliffs in the American Midwest perceived by early travelers from the late seventeenth century onwards was later named the St. Peter Sandstone, whose type section was described on the St. Peter's (now Minnesota) River. Widely separated occurrences were pieced together into a coherent unit by geologists. But the nature and origin of this sandstone were fiercely debated until quite recently. At first thought to be a primordial ocean deposit, or perhaps a vast sinter terrace, it was found to be a recycled sandstone from previous rock units in the region. This study has shown that the very simplicity of the St. Peter Sandstone, a veritable icon of "layer-cake geology," has made it challenging to characterize.

Acknowledgments: My essay on the St. Peter Sandstone was loosely inspired by the historical approach used by David Branagan in his study of the Desert Sandstone of Australia [70].

Conflict of interest: The author declares no conflict of interest.

References

1. Mossler JH. Paleozoic Stratigraphic Nomenclature for Minnesota. Minneapolis: Minnesota Geological Survey; 2008.
2. Runkel AC, Miller JF, McKay RM, et al. High-resolution sequence stratigraphy of lower Paleozoic sheet sandstones in central North America: The role of special conditions of cratonic interiors in development of stratal architecture. Geological Society of America Bulletin. 2007; 119(7-8): 860-881. doi: 10.1130/b26117.1
3. Brick GA. The far shoals of Neptunism: William H. Keating and the St. Peter Sandstone in the American Midwest. Earth Sciences History. 2022; 41(1): 64-76. doi: 10.17704/1944-6187-41.1.64
4. Barnes DA, Ellett KM, Rupp JA. Geologic-carbon-sequestration potential of the Ordovician St. Peter Sandstone, Michigan and Illinois Basins, United States. Environmental Geosciences. 2017; 24(1): 15-49. doi: 10.1306/eg.02071716007
5. Jillson WR. The Saint Peter Sandstone in Kentucky: An Account of the Discovery, Early Surveys, and Regional Geology of This Famous Clastic of the Upper Mississippi Valley Coupled with an Outline of Its Stratigraphic Correlatives in Kentucky to Which Are Added Notes on Its Oil and Gas Possibilities and a Bibliography. Louisville: Standard Printing Co; 1938.
6. Mazzullo JM, Ehrlich R. Grain-shape variation in the St. Peter Sandstone: A record of eolian and fluvial sedimentation of an early Paleozoic cratonic sheet sand. SEPM Journal of Sedimentary Research. 1983; 53. doi: 10.1306/212f8161-2b24-11d7-8648000102c1865d
7. Simo JA, Choi YS, Freiberg PG, et al. Sedimentology, sequence stratigraphy, and paleoceanography of the Middle and Upper Ordovician of eastern Wisconsin. In: Guide to Field Trips in Wisconsin and Adjacent Areas of Minnesota, 31st Annual Meeting, North-Central Section. Geological Society of America; 1997. pp. 95-114.
8. Ojakangas RW, Matsch CL. Minnesota's Geology. Minneapolis: University of Minnesota Press; 2001.
9. Konstantinou A, Wirth KR, Vervoort JD, et al. Provenance of quartz arenites of the early Paleozoic Midcontinent Region, USA. The Journal of Geology. 2014; 122(2): 201-216. doi: 10.1086/675327
10. Kellogg LP. Early Narratives of the Northwest, 1634-1699. New York: Charles Scribner's Sons; 1917.

11. Johnson DS. LaSalle: A Perilous Odyssey from Canada to the Gulf of Mexico. New York: Cooper Square Press, 2002.
12. Hennepin L. Father Louis Hennepin's Description of Louisiana Newly Discovered to the Southwest of New France by Order of the King. Translated by Marion E. Cross. Minneapolis: University of Minnesota Press; 1938.
13. Kett HF. The Past and Present of La Salle County, Illinois. Chicago: H.F. Kett; 1877.
14. Parker J. The Journals of Jonathan Carver and Related Documents 1766-1770. St. Paul: Minnesota Historical Society; 1976.
15. Carver J. Travels Through the Interior Parts of North America. (Facsimile reprint of the third London edition, 1781). Minneapolis, MN: Ross & Haines, Inc.; 1956.
16. Williams JF. A History of the City of Saint Paul, and of the County of Ramsey, Minnesota. St. Paul: Collections of the Minnesota Historical Society; 1876.
17. Lewis H. The Valley of the Mississippi Illustrated. St. Paul: Minnesota Historical Society; 1967.
18. Merrill GP. The First One Hundred Years of American Geology. New York: Hafner Publishing Company; 1969.
19. Swallow GC. The First and Second Annual Reports of the Geological Survey of Missouri. Jefferson City: James Lusk, Printer; 1855.
20. Berkey CP. Paleogeography of Saint Peter time. Geological Society of America Bulletin. 1906; 17(1): 229-250. doi: 10.1130/gsab-17-229
21. Thiel GA. Sedimentary and petrographic analysis of the St. Peter Sandstone. Geological Society of America Bulletin. 1935; 46(4): 559-614. doi: 10.1130/gsab-46-559
22. Keating WH. Narrative of an Expedition to the Source of St. Peter's River, Lake Winnepeek, Lake of the Woods, &c., Performed in the Year 1823. Minneapolis: Ross & Haines, Inc; 1959.
23. Schneer CJ. Ebenezer Emmons and the foundations of American Geology. Isis. 1969; 60(4): 439-450. doi: 10.1086/350535
24. White GW, Slanker BO. Early Geology in the Mississippi Valley. Urbana: University of Illinois; 1962.
25. Eyles JM. G. W. Featherstonhaugh (1780-1866), F.R.S., F.G.S., geologist and traveller. Journal of the Society for the Bibliography of Natural History. 1978; 8(4): 381-395. doi: 10.3366/jsbnh.1978.8.4.381
26. Featherstonhaugh GW. A Canoe Voyage Up the Minnay Sotor. Reprint edition. St. Paul: Minnesota Historical Society; 1970.
27. Yochelson E. The Decline of the use of "Lower Silurian" and the rise of "Ordovician" in U.S. geologic literature. Earth Sciences History. 1997; 16(1): 4-12. doi: 10.17704/eshi.16.1.6844363517t44154
28. Keyes C. Transplantation of English terranal classification to America by David Dale Owen. Pan-American Geologist. 1923; 39(2): 80-94.
29. Owen DD. Preliminary report, containing outlines of the progress of the geological survey of Wisconsin and Iowa, up to October 11, 1847. In: Senate Executive Document 2, 1st Session, 30th. U. S. Congress; 1847. pp. 160-174.
30. Owen DD, Leidy J, Norwood JG, et al. Report of a geological survey of Wisconsin, Iowa, and Minnesota; and incidentally of a portion of Nebraska Territory. Made under instructions from the United States Treasury Department. Philadelphia: Lippincott, Grambo, & Company; 1852. doi: 10.5962/bhl.title.58539
31. Dott RH. James Hall's discovery of the craton. Geologists and Ideas. 1985; 157-167. doi: 10.1130/dnag-cent-v1.157
32. Seddon G. Abraham Gottlob Werner: History and folk-history. Journal of the Geological Society of Australia. 1973; 20(4): 381-395. doi: 10.1080/00167617308728824
33. Adams FD. The Birth and Development of the Geological Sciences. New York: Dover Publications, Inc.; 1954.
34. Brick GA. "White as the Driven Snow": Neptunian Echoes from the Deep Sewers. Journal of Spelean History. 2022; 56(2): 31-35.
35. Ospovat AM. Werner's influence on American geology. Proceedings of the Oklahoma Academy of Science. 1960; 40: 98-103.
36. Lessing P. William Maclure's Wernerian Appalachians. Southeastern Geology. 1999; 38(3): 117-134.
37. Aalto KR. Edwin James' and John Hinton's revisions of Maclure's geologic map of the United States. History of Geo-and Space Sciences. 2012; 3(1): 75-86. doi: 10.5194/hgss-3-75-2012
38. Hazen RM. The founding of geology in America: 1771 to 1818. Geological Society of America Bulletin.1974; 85:12. 1827-1834. doi: 10.1130/0016-7606(1974)85<1827:TFOGIA>2.0.CO;2
39. Maclure W. Observations on the geology of the United States, explanatory of a geological map. Transactions of the American Philosophical Society. 1809; 6: 411. doi: 10.2307/1004821

40. White GW. William Maclure's maps of the geology of the United States. Journal of the Society for the Bibliography of Natural History. 1977; 8(3): 266-269. doi: 10.3366/jsbnh.1977.8.3.266
41. Schneer CJ. William Maclure's Geological Map of the United States. Journal of Geological Education. 1981; 29(5): 241-242. doi: 10.5408/0022-1368-29.5.241
42. Merriam D. Edwin James-Chronicler of geology in the American West. Earth Sciences History. 1994; 13(2): 115-120. doi: 10.17704/eshi.13.2.gn02226010571537
43. James EP. Remarks on the Sandstone and Floetz Trap Formations of the Western Part of the Valley of the Mississippi. Transactions of the American Philosophical Society. 1825; 2: 191. doi: 10.2307/1005059
44. Sardeson FW. The Saint Peter Sandstone. Journal of the Minnesota Academy of Science. 1896; 4(1): 64-88.
45. Greene JC, Burke JG. The Science of Minerals in the Age of Jefferson. Transactions of the American Philosophical Society. 1978; 68(4): 1. doi: 10.2307/1006294
46. Chamberlin TC. Geology of Wisconsin, Survey of 1873-1879. Madison: Commissioners of Public Printing; 1883.
47. Pettijohn FP, Potter PE, Siever R. Geology of Sand and Sandstone. Bloomington: Indiana Geological Survey and Indiana Department of Geology; 1965.
48. Newcomb S. Laboratory Evidence of Silica Solution Supporting Wernerian Theory. Ambix. 1986; 33(2-3): 88-93. doi: 10.1179/amb.1986.33.2-3.88
49. Bischof G. Elements of Chemical and Physical Geology, Volume III. London: Printed for the Cavendish Society by Harrison and Sons; 1859.
50. Amstutz GC. Bischof, Carl Gustav Christoph. In: Gillispie CC (editor). Dictionary of Scientific Biography. New York: Charles Scribner's Sons; 1970; pp. 158-159.
51. Oldroyd DR. The archaean controversy in Britain: Part IV—Some general theoretical and social issues. Annals of Science. 1994; 51(6): 571-592. doi: 10.1080/00033799400200441
52. Tréguer PJ, De La Rocha CL. The World Ocean Silica Cycle. Annual Review of Marine Science. 2013; 5(1): 477-501. doi: 10.1146/annurev-marine-121211-172346
53. Lapham IA. Wisconsin: Its Geography and Topography, History, Geology, and Mineralogy: Together with Brief Sketches of Its Antiquities, Natural History, Soil, Productions, Population, and Government, 2nd ed. Milwaukee: I. A. Hopkins; 1846.
54. Hall J, Whitney JD. Report on the Geological Survey of the State of Iowa, Volume 1. State Printer; 1858.
55. Hall J, Whitney JD. Report on the Geological Survey of the State of Wisconsin, Volume 1. State Printer; 1862.
56. Murrish J. Report on the Geological Survey of the Lead Regions. Wisconsin Geological, Mineralogical, and Agricultural Survey; 1871.
57. Winchell NH. Report on the Geology of Fillmore County. In: Fourth Annual Report of the Geological and Natural History Survey of Minnesota. St. Paul: The Pioneer-Press Company; 1876. pp. 13-74.
58. Law J. Fragmentation and investment in sedimentology. Social Studies of Science. 1980; 10(1): 1-22. doi: 10.1177/030631278001000101
59. Dake CL. The Problem of the St. Peter Sandstone. Rolla: University of Missouri; 1921.
60. Bridge J. Charles Laurence Dake. Bulletin of the American Association of Petroleum Geologists. 1935; 19(1): 143-147.
61. Swain FM. Memorial to George Alfred Thiel (1892-1979). Available online: https://www.geosociety.org/documents/gsa/memorials/v13/Thiel-GA.pdf (accessed on 12 January 2024).
62. Amaral EJ, Pryor WA. Depositional environment of the St. Peter Sandstone deduced by textural analysis. SEPM Journal of Sedimentary Research. 1977; 47. doi: 10.1306/212f70ea-2b24-11d7-8648000102c1865d
63. Tryhorn AD, Ojakangas RW. Sedimentation and petrology of the Upper Precambrian Hinckley Sandstone of east-central Minnesota. In: Sims, P. K., & Morey, G. B. (editors). Geology of Minnesota: A Centennial Volume. St. Paul: Minnesota Geological Survey; 1972. pp. 459-473.
64. Krynine PD. The megascopic study and field classification of sedimentary rocks. The Journal of Geology. 1948; 56(2): 130-165. doi: 10.1086/625492
65. Sorby HC. On the structure and origin of non-calcareous stratified rocks. Proceedings of the Geological Society of London. 1880; 36: 46-92.
66. Folk RL. Henry Clifton Sorby (1826-1908), the founder of petrography. Journal of Geological Education. 1965; 13(2): 43-47. doi: 10.5408/0022-1368-xiii.2.43

67. Klein GDV. Analysis and review of sandstone classifications in the North American geological literature, 1940-1960. Geological Society of America Bulletin. 1963; 74(5): 555-576. doi:10.1130/0016-7606(1963)74[555:AAROSC]2.0.CO;2
68. Johnson CM, Winter BL. Provenance analysis of lower Paleozoic cratonic quartz arenites of the North American midcontinent region: U-Pb and Sm-Nd isotope geochemistry. Geological Society of America Bulletin. 1999; 111(11): 1723-1738. doi:10.1130/0016-7606
69. Tyler SA. Heavy minerals of the Saint Peter Sandstone in Wisconsin. Journal of Sedimentary Research. 1936; 6(2): 55-84. doi: 10.1306/d4268f5e-2b26-11d7-8648000102c1865d
70. Branagan DF. The Desert Sandstone of Australia: A late-nineteenth-century enigma of deposition, fossils, and weathering. Earth Sciences History. 2004; 23(2): 208-256.